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7A.12 MODELS AND LABORATORY EXPERIMENTS OF BUOYANT PUFF DISPERSION IN A CONVECTIVE BOUNDARY LAYER

J.C. Weil

CIRES, University of Colorado
Boulder, Colorado

W.H. Snyder

Mechanical Engineering Department, University of Surrey
Guildford, Surrey, England

R.E. Lawson, Jr.*

ASMD, ARL, National Oceanic and Atmospheric Administration
Research Triangle Park, North Carolina

R.S. Thompson

AMD, NERL, U.S. Environmental Protection Agency
Research Triangle Park, North Carolina

M.S. Shipman

Geophex, Ltd.
Raleigh, North Carolina

1. INTRODUCTION

Buoyant puffs or thermals are generated by the sudden release of heat in the atmosphere, e.g., from an explosion. Much is known about the rise and spread of thermals in a nonturbulent environment from both models and laboratory experiments (e.g., Turner, 1979) and recent experiments have added to our knowledge of thermals in a neutral environment capped by a stable layer (Thompson et al., 1998). However, there have been relatively few studies of buoyant puff behavior in a turbulent environment such as the convective boundary layer (CBL). The latter is pertinent to a number of atmospheric problems. In this paper, we present: 1) a simple model of buoyant puff dispersion in the CBL, 2) results from experiments on puff dispersion in a laboratory convection tank, and 3) a brief comparison of the two. The experiments—the first on buoyant puffs in a convection tank—were conducted at the U.S. EPA Fluid Modeling Facility.

This study is motivated by the need to dispose of obsolete munitions and ordnance at Department of Defense (DOD) and Department of Energy (DOE) facilities. The most widely-used disposal method is open burning (OB) and open detonation (OD) in an earthen pit. Since OBOD generates air pollutants, any facility using this method must meet source permit requirements and demonstrate a low risk to human health and the environment. This requires an appropriate dispersion model to estimate ambient air concentrations, dosage, surface deposition, etc. In particular, estimates of the peak ground-level concentrations (GLCs) are required for averaging times ranging from a few minutes to an hour.

In earlier work (Weil et al., 1996), we presented an overview of a model being developed for OBOD sources, which are unique in having instantanteous or short-duration releases of buoyant material. The model includes: 1) a uniform treatment of dispersion as the release varies from instantaneous to continuous, 2) puff and plume rise estimated from entrainment models, 3) relative and total dispersion based on similarity scaling concepts for the planetary boundary layer (PBL), and 4) preprocessed meteorological variables (surface heat flux, PBL depth, etc) for estimating mean winds

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* On assignment to NERL, U.S. Environmental Protection Agency.

Corresponding author address: J.C. Weil, NCAR, P.O. Box 3000, Boulder, CO 80307 and turbulence in the PBL. This paper focuses on puff releases in the CBL because OBOD activities are currently restricted to daytime convective periods. However, the overall OBOD model addresses all PBL types including stable conditions.

2. DISPERSION MODEL

The dispersion of a buoyant puff is a random phenomenon owing to the stochastic nature of turbulence in the PBL. This means that the concentration observed at some downwind receptor is a random variable and should be estimated statistically through a probability distribution. The distribution can be parameterized using an analytical form such as a gamma probability density function (p.d.f.) and requires two variables to characterize it—the ensemble-mean concentration C and the root-mean-square (rms) concentration fluctuation σ_c. The peak concentration can then be defined by a specified percentile value of the cumulative probability, e.g., the 99.9th percentile level. In the following, we discuss approaches for estimating C, σ_c, puff rise, and dispersion.

A Gaussian puff model is adopted for the C field relative to the puff centroid. In an absolute reference frame or one that includes the puff "wandering" due to the large CBL eddies, we adopt a meandering puff model based on Gifford's (1959) approach. The puff meander or centroid displacement in the x (downwind), y (crosswind), and z (vertical) directions is estimated from the p.d.f.s of the turbulent velocity fluctuations (u, v, w) in those directions. In the CBL, the p.d.f.s of the u and v components are assumed to be Gaussian whereas the w p.d.f., p_w, is taken to be positively skewed in accord with observations (Weil, 1988). The p.d.f. is parameterized by the superposition of two Gaussian distributions.

The C field due to an ensemble of meandering puffs is derived from the velocity p.d.f.s following the same approach as applied to continuous plumes (Weil, 1988). The vertical displacements due to the mean puff rise and the random w in the CBL are superposed. The resulting expression for C is

$$C = \frac{Q}{(2\pi)^{3/2}\sigma_x\sigma_y} \exp\left(-\frac{(x-Ut)^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}\right) \times \sum_{j=1}^{2} \frac{\lambda_j}{\sigma_{zj}} \exp\left(-\frac{(z-h_e-z_{cj})^2}{2\sigma_{zj}^2}\right) , \quad (1)$$

where Q is the pollutant mass released, U is the mean wind speed, t is time, h_e is the effective puff height, σ_x and σ_y are the puff dispersion in the x and y directions, $\sigma_{zj} = \sigma_j x/U$, and $z_{cj} = \overline{w_j} x/U$ with $j = 1, 2$. The λ_j, $\overline{w_j}$, and σ_j, $(j = 1, 2)$ are the weight, mean velocity, and standard deviation of each Gaussian p.d.f. comprising p_w. Here, $h_e = h_s + z_p(t)$, where h_s is the source height and z_p is the puff rise due to buoyancy. Equation (1) applies for short distances such that the plume interaction with the ground or elevated inversion is weak. The complete expression for C includes multiple puff reflections at the ground and PBL top, $z = z_i$.

To find σ_c, we first estimate the mean square concentration $\langle c^2 \rangle$, where the brackets denote an ensemble average, and then obtain $\sigma_c = (\langle c^2 \rangle - C^2)^{1/2}$. Using the bi-Gaussian form of p_w, we find the expression for $\langle c^2 \rangle$ to be

$$\langle c^2 \rangle = \frac{Q^2}{(2\pi)^3\sigma_r^3\sigma_{xe}\sigma_{ye}} \exp\left(-\frac{(x-Ut)^2}{\sigma_{xe}^2} - \frac{y^2}{\sigma_{ye}^2}\right) \times \sum_{j=1}^{2} \frac{\lambda_j}{\sigma_{zej}} \exp\left(-\frac{(z-h_e-z_{cj})^2}{\sigma_{zej}^2}\right) , \quad (2)$$

where σ_r is the puff relative dispersion, $\sigma_{xe} = (\sigma_r^2 + 2\sigma_x^2)^{1/2}$, $\sigma_{ye} = (\sigma_r^2 + 2\sigma_y^2)^{1/2}$, and $\sigma_{zej} = (\sigma_r^2 + 2\sigma_{zj}^2)^{1/2}$ with $j = 1$ or 2. Equation (2) applies to short distances such that the puff interaction with the boundaries is weak. The complete expression for $\langle c^2 \rangle$ includes reflections at $z = 0$ and z_i.

The puff rise is obtained from a conventional entrainment model (e.g., Turner, 1979) in which one solves equations governing the time rate of change of the total puff volume, momentum, and energy or buoyancy. In a near-neutral environment, the predicted rise is

$$z_p = -z_{pv} + \left(z_{pv}^4 + \frac{2F_T t^2}{\beta^3 k_v (4\pi/3)}\right)^{1/4} , \quad (3)$$

where $z_{pv} = r_o/\beta$ is a virtual source height, r_o is the source radius, β is an entrainment coefficient, k_v $(= 1.5)$ is an apparent mass coefficient, and F_T is the source buoyancy. $F_T = (4\pi/3) r_o^3 g(\rho_a - \rho_o)/\rho_a$, where g is the gravitational acceleration and ρ_o and ρ_a are the source and ambient densities, respectively. The model also predicts the puff radius r to vary as $r = r_o + \beta z_p$.

For puffs, the relative dispersion is dominated by the buoyancy-induced growth at short times, $t < T_L$ where T_L is the Lagrangian integral timescale. The dispersion is given by $\sigma_r = \sigma_{rb} = r/\sqrt{2}$ and can be approximated by $\sigma_{rb} \simeq 0.5\beta^{1/4} F_T^{1/4} t^{1/2}$. In the following, we assume $\sigma_r = \sigma_{rb}$ for all t, but note that ambient turbulence may be important at intermediate and long times. A parameterization of σ_r for ambient turbulence (Weil et al., 1996) will be considered in the future.

The absolute dispersion due to ambient turbulence, σ_{xa} and σ_{ya}, is required and can be obtained from a parameterization of Taylor's theory:

$\sigma_{ya} = \sigma_v t/(1 + 0.5t/T_{Ly})^{1/2}$ and similarly for σ_{xa}. For the CBL, we adopt $T_{Lx} = T_{Ly} = 0.7z_i/w_*$ (Weil, 1988), where z_i is the CBL depth and w_* is the convective velocity scale, and evaluate the rms turbulence velocities, σ_u and σ_v, from the σ_y measurements discussed below. The total dispersion is given by $\sigma_y = (\sigma_r^2 + \sigma_{ya}^2)^{1/2}$.

3. EXPERIMENTS

The experiments were conducted in a convection tank that measured about 124 cm on a side, was filled with water to a depth of 34 cm, and had an initial stratification aloft of 1°C/cm. The convection was driven by an electrically-heated bottom surface that yielded a $z_i = 18$ cm and $w_* = 0.71$ cm/s at the time of the measurements. The source was a squat cylinder ($r_o = 0.95$ cm) with covers on the top and bottom to contain a buoyant water - alcohol mixture with a small amount of Rhodamine dye; the dye fluoresced when excited by laser light. The covers were quickly removed at $t = 0$ to expose the source fluid to the environment, and about 5 s later, the cylinder was moved laterally away and eventually out of the tank.

A laser was mounted on a table alongside the tank and illuminated a y - z cross section along the tank centerplane ($x = 0$). Video images of the fluorescent dye were taken from a camera with its axis normal to this plane. In each realization of an experiment, 90 cross-sectional images were recorded over the span $0 \leq t \leq 99$ s and at intervals increasing geometrically from 0.5 s to 5 s. From $t = 63$ s to 86s, the laser sheet was swept rapidly through the puff (along x) to obtain images every 0.5 s and used to check mass conservation.

An experiment was defined by the value of the dimensionless buoyancy given by $F_{T*} = F_T/(w_*^2 z_i^2)$, which was 0.044, 0.17, and 0.70 for the three experiments conducted. These F_{T*}'s corresponded to full-scale detonations of 1.5, 6, and 24 tons TNT for typical CBL conditions ($z_i = 1000$ m, $w_* = 2$ m/s). For each experiment, 33 realizations or repeats were obtained to define the ensemble-average behavior. Further information on the experimental approach can be found in Lawson et al. (1998).

4. RESULTS

In the following, we discuss features of the puff spatial statistics and concentration fields. We adopt convective scaling of dispersion wherein z_i and w_* are the relevant turbulence length and velocity scales. Puff variables are shown as a function of the dimensionless time t/t_*, where $t_* = z_i/w_*$ is the convective time scale. For a typical full-scale CBL ($z_i = 1000$ m, $w_* = 2$ m/s), $t_* = 500$ s or ~ 8 min whereas it is only 25 s in the tank.

Figure 1 presents the dimensionless mean puff height $\overline{z}/z_i$ and shows that the laboratory data vary systematically with t/t_* and F_{T*}. In all cases, the $\overline{z}$ overshoots the equilibrium height ($0.5z_i$) for a well-mixed distribution; this occurs due to the vertical momentum generated by the source buoyancy. For $F_{T*} = 0.044$ and 0.17, the overshoot is temporary since the equilibrium $\overline{z}$ (at $t/t_* \simeq 4$) is only slightly greater than $0.5z_i$, but for the highest buoyancy, the equilibrium $\overline{z}$ is near $0.9z_i$. In the first two cases, the buoyancy is insufficient to overcome the strong mixing by downdrafts, whereas in the third case (PFH), it is sufficient.

The modeled mean height is shown for $\beta = 0.3$ and found to agree rather well with the data in the initial rise region. This β, based on the centroid height, is in the range of values found in the literature.

Figure 2 shows that the measured lateral dispersion of the puffs varies in an orderly way with t/t_* and buoyancy. One can see that σ_y initially varies like $\sigma_y/z_i \propto (t/t_*)^{1/2}$ as given by the prediction $\sigma_y/z_i \simeq \sigma_{rb}/z_i \simeq 0.36F_*^{1/4}(t/t_*)^{1/2}$; the t/t_* range over which this holds increases with F_{T*}. The lines are parameterizations of the form $\sigma_y = (\sigma_{rb}^2 + \sigma_{ya}^2)^{1/2}$, in which we have used $\sigma_u = \sigma_v = 0.35w_*$. This σ_v/w_* appears

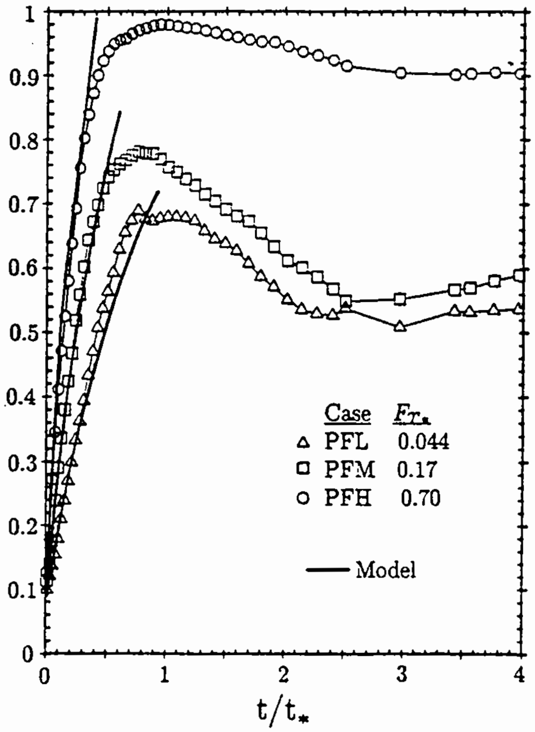

Fig. 1. Dimensionless mean puff height as a function of the dimensionless time.

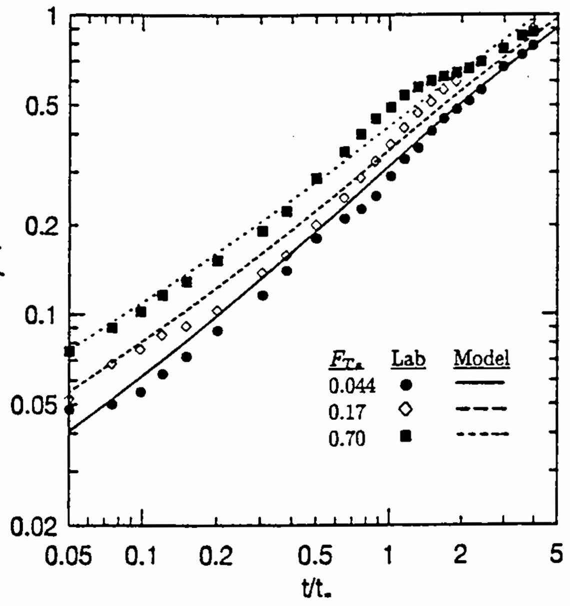

Fig. 2. Dimensionless lateral dispersion versus t/t_*.

small by comparison with field observations in CBLs having a nonzero mean wind ($\sigma_v/w_* \simeq 0.6$; Weil, 1988). However, the above value is more compatible with the σ_v/w_* in zero-wind or free convection conditions as determined from large-eddy simulations (Schmidt and Schumann, 1989; $\sigma_v/w_* \simeq 0.4$) and earlier tank experiments (Willis and Deardorff, 1974; $\sigma_v/w_* \simeq 0.4$ - 0.45). The parameterization gives an approximate fit to the data and orders it by F_{T*}.

The dimensionless mean concentration Cz_i^3/Q as a function of t/t_* is shown in Fig. 3 for the lowest (PFL) and highest (PFH) puff buoyancies. The time histories were obtained at various heights above the bottom center of the tank. As can be seen, there is some data scatter, which is probably the result of an insufficient number of realizations. However, this does not mask the overall trend of a generally decreasing concentration with time due to the expanding puff. For case PFL, the greatest variation in concentration among the different heights occurs for $0.5 \leq t/t_* \leq 2$, with the values of C at $z/z_i = 0.1$ being the lowest; this is attributed to the overshoot of the puff centroid in this time interval (Fig. 1). For larger t/t_* (> 2), the data from all heights collapse to essentially the same curve as the puff tends to a vertically well-mixed distribution.

By comparison with Fig. 3a, there are two obvious differences in the concentration history for the high buoyancy case (Fig. 3b). First, the C at $z/z_i = 1$ is about an order of magnitude greater than the values within the mixed layer ($z/z_i < 1$). This is due to the significant puff lofting or the maintenance of a $\bar{z}$ near z_i (Fig. 1). Second, the concentrations within the mixed layer are about an order of magnitude smaller than those at the same

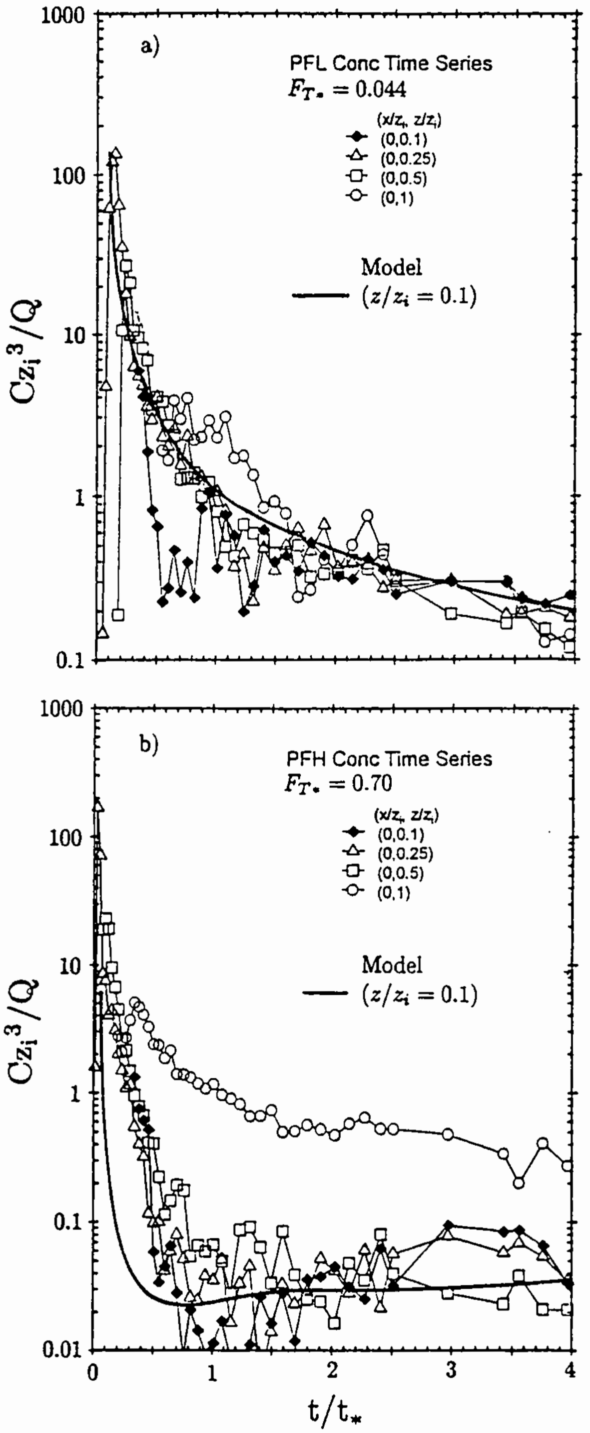

Fig. 3. Dimensionless concentration at four heights as a function of t/t_*.

heights for the low buoyancy case (Fig. 3a). Again, the lower concentrations result from the significant puff lofting for case PFH.

A preliminary comparison of the modeled concentration history at $z/z_i = 0.1$ with the data is shown in Figs. 3a and 3b. For case PFL, the model curve captures the correct overall trend. For $0.4 < t/t_* < 2$, the model overestimation is probably real even though the data are scattered and the measured σ_c/C is typically 2 - 3 in this time interval. The lower observed C is probably due to the $\overline{z}$ overshoot and reduced σ_z, which are not adequately replicated by the model. For the high buoyancy case (Fig. 3b), the model also captures the overall data trend for $z/z_i = 0.1$ and the correct order of magnitude of C for $0.5 \leq t/t_* \leq 4$ but differs by as much as a factor of 3 from the data. This is partially due to insufficient averaging (realizations) and also to model limitations. More detailed comparisons and model improvements will be made in the future.

5. CONCLUDING REMARKS

This paper presented a simple model of buoyant puff dispersion in the CBL and new experimental results on puff dispersion in a laboratory convection tank. The dimensionless buoyancies F_{T*} of the experimental puffs were 0.044, 0.17, and 0.70, which corresponded to full-scale detonations of 1.5, 6, and 24 tons TNT. The data on $\overline{z}$, σ_y, and C revealed important buoyancy effects such as puff lofting. Although the mean concentrations exhibited some scatter due to insufficient realizations, the overall trends with t, z, and F_T were clearly demonstrated. A preliminary comparison of the model and data showed encouraging results and suggested some areas for improvement, e.g., the treatment of lofting. The laboratory data already have proven quite useful in the model development and should continue to do so in the future. By comparison with field observations, the experiments offer a unique, low-cost alternative for obtaining the ensemble-mean puff properties under controlled conditions.

6. DISCLAIMER

This paper has been reviewed in accordance with the U.S. Environmental Protection Agency's peer and administrative review policies and approved for presentation and publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

7. ACKNOWLEDGMENTS

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15. SUPPLEMENTARY NOTES

16. ABSTRACT

Buoyant puffs or thermals are generated by the sudden release of heat in the atmosphere, e.g., from an explosion. Much is known about the rise and spread of thermals in a nonturbulent environment from both models and laboratory experiments (e.g., Turner, 1979) and recent experiments have added to our knowledge of thermals in a neutral environment capped by a stable layer (Thompson et al., 1998). However, there have been relatively few studies of buoyant puff behavior in a turbulent environment such as the convective boundary layer (CBL). The latter is pertinent to a number of atmospheric problems. In this paper, we present: 1) a simple model of buoyant puff dispersion in the CBL, 2) results from experiments on puff dispersion in a laboratory convection tank, and 3) a brief comparison of the two. The experiments-the first on buoyant puffs in a convection tank-were conducted at the U.S. EPA Fluid Modeling Facility.

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